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Effect of Fuel Properties on the Specific Thrust of a Ramjet Engine

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ABSTRACT

Various aspects of specific thrust in ramjet propulsion have been considered. It is shown that while the peak specific impulse of ideal ramjet is theoretically obtained for fuel/air ratio $f \rightarrow 0$, the specific thrust which determines the thrust level of a given engine at certain operating conditions, increases with increasing fuel/air ratio up to (approximately) the stoichiometric ratio. Furthermore, in general, the specific thrust is related to the heat release per unit mass of air fq_R, where the theoretical maximum is approximately proportional to its square root in stoichiometric conditions, $f_{st}q_R$. This can be the basis for selecting an appropriate fuel according to its potential specific thrust. It should be noted that certain metals such as magnesium, aluminum, and zirconium can provide about three-times higher specific heat release than hydrocarbons or hydrogen. Thus, these may be the better candidates for missions requiring high specific thrusts.

Keywords: Ramjet engine, specific thrust, specific impulse, ramjet propulsion, fuel-air ratio, specific heat release, fuels, fuel efficiency, fuel rich propellant

1. INTRODUCTION

Ramjet performance is greatly affected by flight parameters as well as by fuel properties. The main parameter representing the energetic performance is the specific impulse,

$$I_{sp} = F \big/ \left(\dot{m}_f \, g_o \right) \qquad (1)$$

which is desired to be as high as possible, and the thrust-specific fuel consumption

$$TSFC = \dot{m}_f \big/ F = 1 \big/ \left(I_{sp} \, g_o \right) \qquad (2)$$

which gives equivalent information and is sought to be as low as possible. Here, F is the thrust and m_f the fuel mass flow rate.

Analysis of the ideal ramjet cycle[1] reveals the following: (i) I_{sp} of an ideal ramjet has a local maximum at the conventional supersonic flight range, typically between Mach number 2.2 and Mach number 3.5, (ii) for any operating conditions, the lower the fuel/air ratio, $f = m_f/m_a$, the higher is the specific impulse of the ideal ramjet. Theoretically, the peak I_{sp} at any given conditions is obtained for $f \rightarrow 0$, (iii) higher fuel energy (heat of combustion per unit mass of fuel) q_R, results in a higher specific impulse. Theoretically, the peak specific impulse of an ideal ramjet is directly proportional to q_R.

The above-mentioned characteristics are demonstrated in Fig. 1, presenting specific impulse versus Mach number of an ideal ramjet employing a representative fuel, hydrocarbon, with q_R = 10.0

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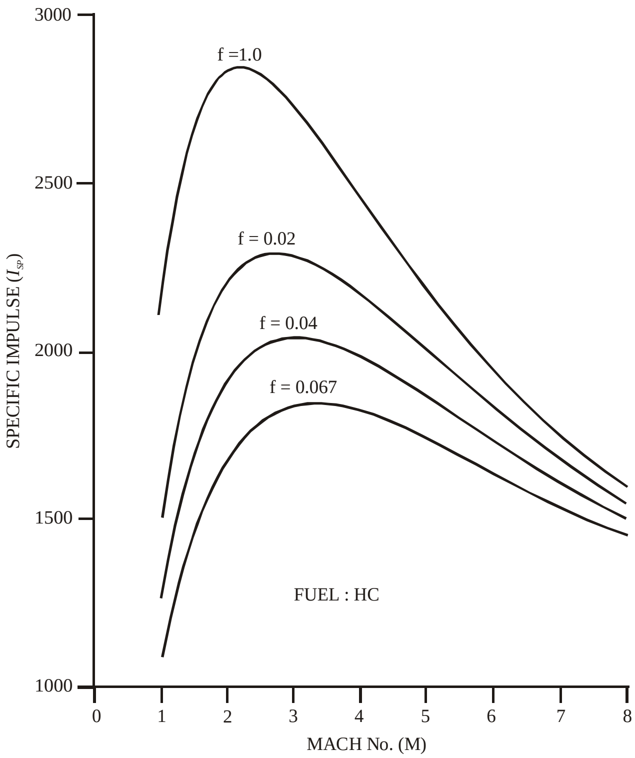

Figure 1. Specific impulse *vs* Mach number with *f* as a parameter for an ideal ramjet employing hydrocarbon.

kcal/g fuel (41.85 kJ/g fuel), with the fuel/air ratio as a parameter.

Another aspect of interest, particularly for volume-limited systems, is the energy density $\rho_f q_R$ or $\rho_f I_{sp}$, which indicates the energy contained in a unit volume of fuel.

The specific impulse indicates the energetic performance of the fuel without relating it to the thrust level. However, seeking the highest specific impulse and ignoring other system requirements, may not be realistic. For instance, when using a certain fuel at some given flight conditions, I_{sp} generally increases by reducing f. The result may be a too low thrust (and of course zero thrust for $f \rightarrow 0$). The situation is even worse when accounting for a non-ideal operation.

When a ramjet engine of given configuration and inlet capture area is designed for specific flight conditions, the incoming air flow rate is determined. While the air flow rate is fixed, the thrust generated is characterised by the so-called specific thrust F/m_a, namely, the thrust per unit mass flow rate of air[2-4]. It depends on the energy that can be provided to the air, which is dependent itself on the energetic and chemical properties of the fuel, particularly the heat of combustion per unit mass of fuel, and the fuel/air ratio.

Increased fuel/air ratio is required when higher acceleration or higher terminal velocity are sought. This may be the typical operating mode of ramjet engines propelling surface-to-air or air-to-air missiles as well as gun-launched projectiles. It is suspected that system requirements often lead to a design point at the stoichiometric fuel/air ratio, which approximately yields the highest thrust at given operating conditions, in spite of the lower specific impulse compared to operations at leaner fuel/air ratios.

Another parameter is the net-jet thrust coefficient C_F .

$$C_F = F \Big/ \left(\frac{1}{2} \rho_a u_a^2 A_{ref} \right) \tag{3}$$

also gives an indication of the thrust level related to the dynamic pressure and a reference area (eg, the vehicle cross-section), where u_a is the flight (or relative air) velocity.

The objective of this study is to discuss the main aspects of the specific thrust, and to reveal its dependence on fuel properties and other parameters.

2. SPECIFIC THRUST

To gain insight and physical understanding, the specific thrust, using initially the ideal ramjet cycle is considered. The ideal cycle assumes ideal gas of constant properties throughout the engine, isentropic compression (to stagnation pressure, P_c) and expansion (to the ambient pressure, P_a), combustion process at constant total (stagnation) pressure, P_c , and heat addition in direct proportion to the fuel/air ratio, f.

Under these conditions, the specific thrust is:

$$F/\dot{m}_a = (1+f)u_e - u_a \tag{4}$$

Introducing the air-specific impulse, $I_{sp,a}$, the specific thrust can be expressed as

$$F/\dot{m}_a = I_{sp,a}\, g_o \tag{5}$$

The exit velocity, u_e is

$$u_e = \sqrt{2c_pT_c\left[1-\left(P_e/P_c\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{6}$$

where, T_C is the stagnation temperature in the combustion chamber, and $P_e = P_a$.

Heat balance in the combustion chamber per unit mass of air (the index 0 denotes stagnation properties):

$$(1+F)c_pT_c = c_pT_{0a} + fq_R \tag{7}$$

Hence

$$c_pT_c = \frac{c_pT_{0a} + fq_R}{(1+F)} \tag{8}$$

It can be shown that in the ideal ramjet

$$\frac{u_e}{u_a} = \sqrt{\frac{T_c}{T_{0a}}} \tag{9}$$

Substituting Eqns (8) and (9) in Eqn (4), one obtains:

$$\frac{F}{m_a} = u_a\left[\sqrt{1+f}\cdot\sqrt{1+\frac{fq_R}{c_pT_{0a}}}-1\right] \tag{10}$$

In the specific case of $f << 1$ and $fq_R >> c_pT_{0a}$ (which is more realistic for relatively low flight Mach numbers), one can show that the specific heat capacity in the combustion chamber c_pT_c, is approximately equal to the specific heat release fq_R (heat release per unit mass of air) for a given flight velocity. In this case:

$$\frac{F}{\dot{m}_a} \tilde{\propto} \sqrt{fq_R} \tag{11}$$

Even though in actual cases, the dependence of the specific thrust on the specific heat release is more complex, the specific heat release has a major effect on the specific thrust.

The product of $f_{st}\, q_R$ indicates the maximum theoretical specific heat release that can be provided by each fuel, and is closely related to the specific heat capacity of the combustion products in the combustion chamber.

One may conclude, that when looking for a higher specific thrust, two main aspects have to be considered: (i) for a given fuel, the stoichiometric fuel/air ratio (and sometimes even a little higher)

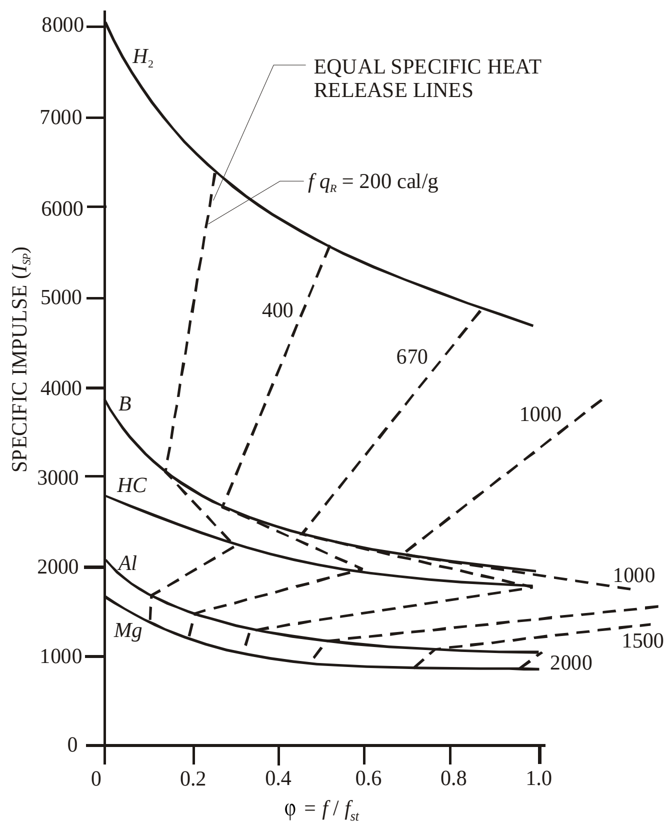

Figure 2. Specific impulse vs φ plots connected with equal specific heat release lines for five representative fuels.

Table 1. Chemical energy properties of selected fuels

Fuel candidate	ρ [g/cm^3]	Main oxides	$q_R{}^a$ [kcal/g fuel]	ρq_R [kcal/cm^3 fuel]	f_{st}	$f_{st}\, q_R$ [kcal/g air]
H_2 (liquid)	0.071	H_2O(g)	28.9	2.1	0.029	0.84
Hydrocarbon	0.90	H_2O, CO_2	10.0	9.0	0.067	0.67
Li	0.54	$Li_2\,O$(l)	9.52	5.1	0.201	1.91
B	2.35	B_2O_3(l)	13.87	32.6	0.104	1.44
C (graphite)	2.25	CO_2(g)	7.83	17.6	0.087	0.68
Mg	1.74	MgO(s)	5.91	10.3	0.352	2.08
Al	2.70	Al_2O_3(s)	7.41	20.1	0.260	1.93
Ti	4.5	TiO_2(s)	4.71	21.2	0.347	1.63
Zr	6.49	ZrO_2(s)^b	2.87	18.6	0.661	1.90
LiH	0.82	Li_2O,H_2O	9.23	7.6	0.115	1.06
MgH_2	1.42	MgO,H_2O	6.96	9.9	0.191	1.33
$Al\,H_3$	1.5	Al_2O_3,H_2O	9.33	14.0	0.145	1.35
$Ti\,H_2$	3.9	TiO_2,H_2O	5.11	19.9	0.241	1.23

a Main oxide is considered, b At high φ, ZrO and ZrN are also generated.

should be employed, (ii) selection of appropriate fuels should basically be done according to their maximum heat release per unit mass of air, ie, theoretically $f_{st}\, q_R$.

3. RESULTS & DISCUSSION

Figure 2. presents[1] equal specific heat release lines for five different fuels, connecting the corresponding points on I_{sp} versus φ plots of ideal ramjets. It reveals, that the two most common ramjet fuels, hydrocarbon and hydrogen, are in the lowest range of theoretical specific heat release, 0.67 and 0.84 kcal/g air, respectively (carbon presents a similar value, 0.68 kcal/g air). On the other hand, the selected metallic elements yield much higher specific heat release.

The fact that metals may yield some advantageous energetic characteristics was noted by Goroshin[5] *et al.*, although their consideration was mainly associated with energy-density aspects.

Table 1 reveals chemical energy properties of the fuels[1,6] included in Fig. 2, as well as some other elements and metal hydrides. Additional details on other fuel candidates can be found in the paper by Gany[7], *et al*.

In addition to the information included in Fig. 2, Table 1 shows that metal hydrides seem to be inferior to the corresponding pure metals as regards the theoretical specific heat release.

Figure 3 presents a broader picture of the maximum theoretical heat release $f_{st}q_R$ of the first 30 elements of the periodic table. One can note that like other properties, the theoretical specific heat release of the elements varies in cycles.

Figures 4 to 9 present thermochemical calculations of specific impulse I_{sp} and specific thrust F/m_a of six common fuel ingredients, hydrogen, hydrocarbon, boron, magnesium, aluminium, and zirconium, respectively, for three different flight Mach numbers: Mach numbers 2.236 (which is theoretically Mach number for peak specific impulse of an ideal ramjet at $f\rightarrow 0$), Mach numbers 3 and 4. Corresponding total chamber pressures of 10 bar, 22 bar, and 60 bar, representing inlet pressure recovery of approximately 85 per cent, 60 per cent and 40 per cent, respectively, chemical equilibrium in the combustion chamber, and nozzle expansion to atmospheric pressure at sea level were used in the calculations. From these figures, one can see that, qualitatively the specific heat release $f_{st}q_R$ indicates the trend of the relative maximum specific thrust of the different fuels. Furthermore, correlating the specific thrust obtained from the thermochemical calculations for the stoichiometric fuel/air ratio (equivalence ratio $\varphi = f/f_{st} = 1$), one may conclude that the peak specific

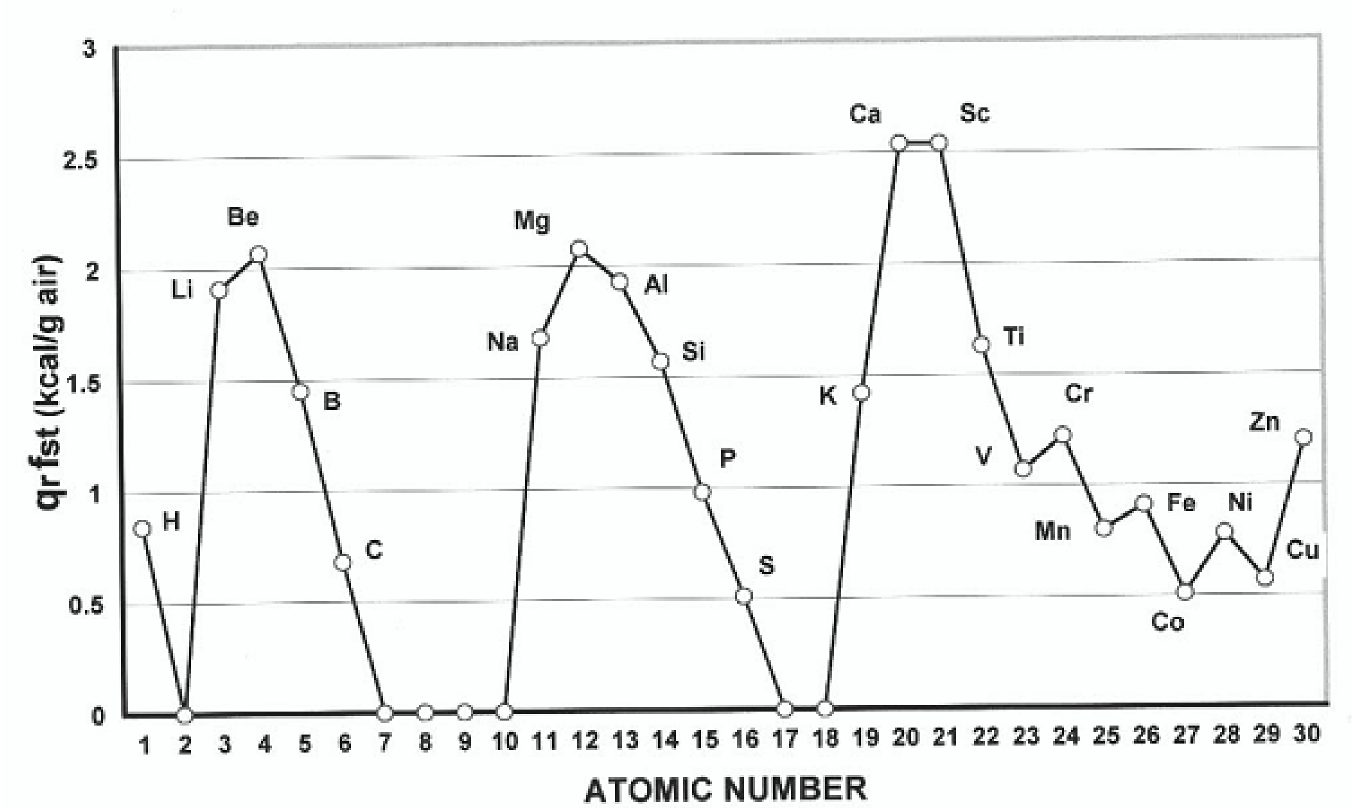

Figure 3. Maximum theoretical specific heat release $f_{st}\,q_R$ of different elements of the periodic table

thrust of the different fuels is approximately proportional to the square root of the specific heat release, as was indicated by Eqn (11):

$$\left(\frac{F}{\dot{m}_a}\right)_{\varphi=1} \tilde{\propto} \sqrt{f_{st} q_R} \tag{12}$$

There is one prominent exception demonstrating remarkably high specific thrust, ie, zirconium (see Fig. 9). The main reason is that at high equivalence ratios, particularly for φ>1, other reactions of Zr with air take place, forming ZrO and ZrN in addition to ZrO_2 and providing additional energy to the available incoming air. It may however be noted that the specific impulse of Zr is substantially lower than that of Al and Mg.

From Fig. 2, Table 1, and Figs 4-9, one can see that among the elements of practical use in

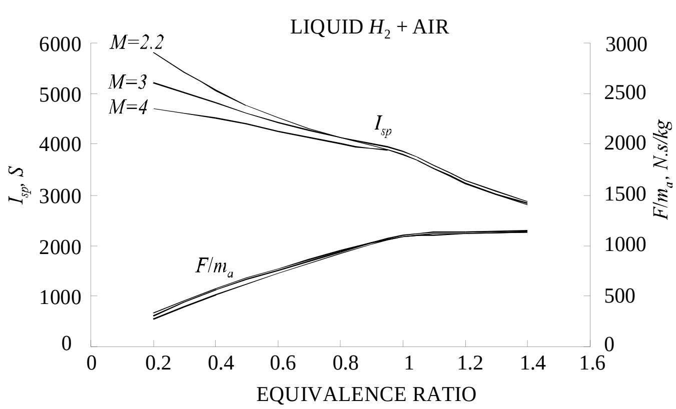

Figure 4. Calculation of specific thrust and specific impulse of a ramjet employing liquid H_2 as fuel at different flight Mach numbers at sea level.

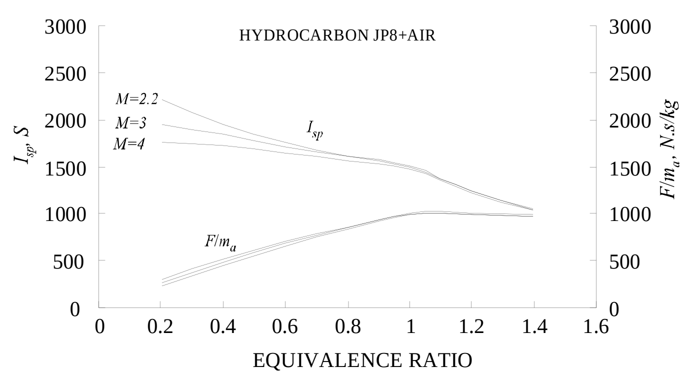

Figure 5. Calculation of specific thrust and specific impulse of a ramjet employing hydrocarbon (JP8) as fuel at different flight Mach numbers at sea level.

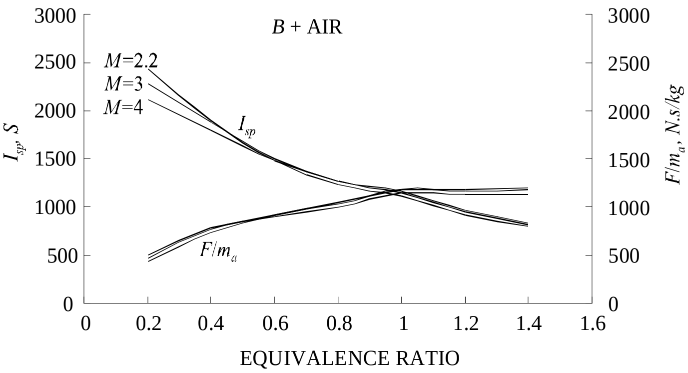

Figure 6. Calculation of specific thrust and specific impulse of a ramjet employing *B* as fuel at different flight Mach numbers at sea level.

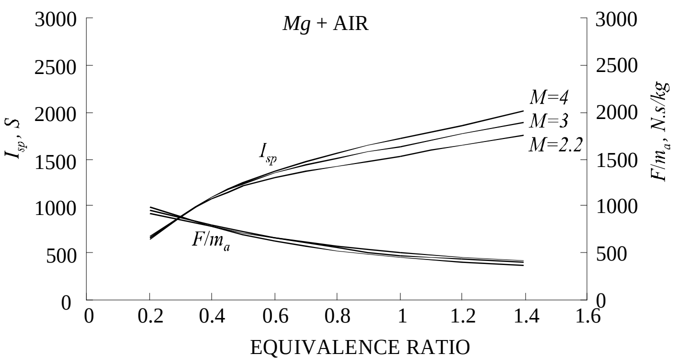

Figure 7. Calculation of specific thrust and specific impulse of a ramjet employing *Mg* as fuel at different flight Mach numbers at sea level.

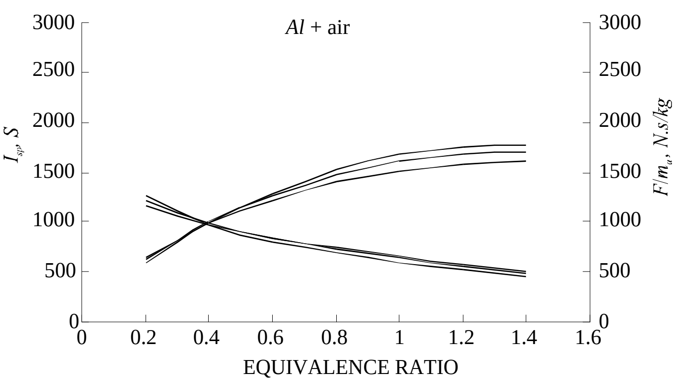

Figure 8. Calculation of specific thrust and specific impulse of a ramjet employing *Al* as fuel at different flight Mach numbers at sea level.

propulsion, magnesium, aluminum, and zirconium appear at the peaks of the specific heat release cycles, providing $f_{st}q_R$ of almost three-times higher than hydrocarbons, hence these are probably the best practical fuel candidates for high specific thrust missions. Beryllium, calcium and scandium also

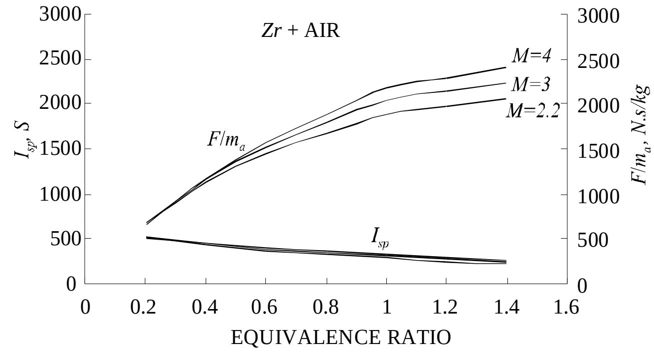

Figure 9. Calculation of specific thrust and specific impulse of a ramjet employing *Zr* as fuel at different flight Mach numbers at sea level.

reveal very high values of specific heat release, but their use seems to be impractical. Beryllium and its compounds are very toxic, scandium is relatively rare and expensive, and pure calcium is chemically difficult to handle.

One may investigate in another direction for fuels at high specific thrust: the use of fuel-rich

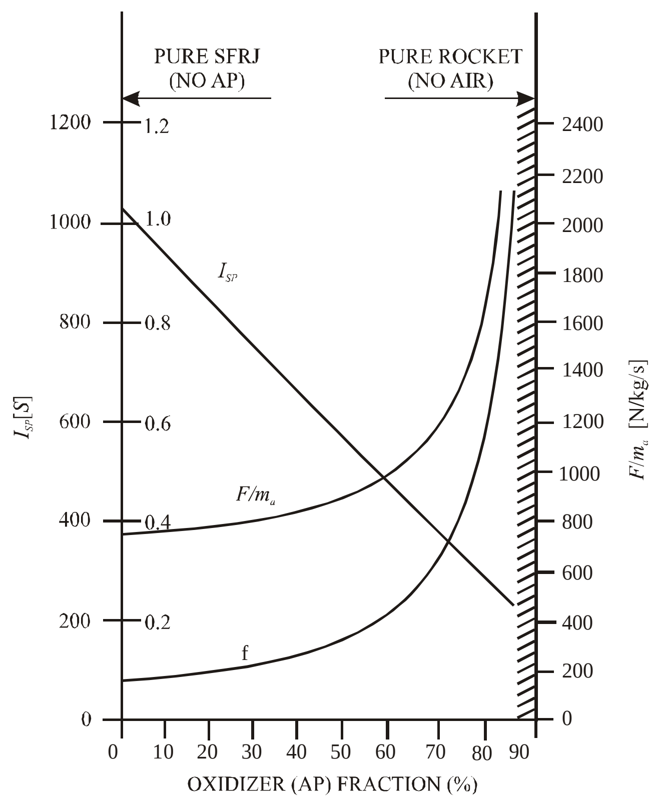

Figure 10. Calculation of I_{sp}, $F/\dot{m}_a$ and *f* versus oxidiser (AP) content in an SFRJ employing an HC fuel-rich propellant, assuming Pitot inlet and 90 per cent combustion efficiency at sea level.

solid propellants. A pure hydrocarbon ramjet fuel may have no oxidiser at all. However, when adding an oxidiser, the stoichiometric fuel/air ratio increases, implying an increase of the specific thrust while decreasing the specific impulse. Fig. 10 reveals the predicted performance[8] of a solid fuel ramjet (SFRJ) employing a fuel-rich propellant versus the oxidiser mass fraction, from a pure hydrocarbon fuel (zero oxidiser) to over 80 percent oxidiser, which is almost its percentage in a rocket's solid propellant. One can see that while the specific impulse decreases almost linearly with the addition of oxidiser, the specific thrust increases slowly and reaches to high values only for very high oxidiser mass fractions, where the specific impulse is low. In Fig. 9, the calculations are performed for an ammonium perchlorate-based propellant, flight Mach number 3, stagnation pressure losses related to Pitot inlet, and combustion efficiency of 90 per cent. These conditions result in somewhat reduced performance compared to the previous calculations that assumed a little better pressure recovery and chemical equilibrium conditions in the combustion chamber. Nevertheless, the results indicate that specific thrust levels similar to those of some metallic fuels (ie, above 1500 N/kg/s) would be obtainable only for hydrocarbon fuel-rich propellants of AP content higher than 70 per cent at the expense of low I_{sp}, of about 300 s (compared to over 600 s for *Al* and over 450 s for *Mg*).

4. CONCLUSIONS

The study deals with the specific thrust of ramjet engines, correlating it to the relevant fuel properties. It is shown that the specific thrust, which indicates the relative thrust level of a given system, is approximately proportional to the square root of the specific heat capacity of the combustion gases, and can be approximately related to the square root of the specific heat release of the fuel, yielding maximum theoretical value for stoichiometric conditions, ie

$$F/m_a \ \overline{\alpha} \sqrt{f_{st} \cdot q_R}$$

Selecting fuel candidates for high specific thrust missions reveals that $f_{st} q_R$ of the different elements of the periodic table varies in cycles. Certain metals exhibit remarkably high specific heat release of about three-times the value of hydrocarbon fuels. Of the peak value elements, *Mg*, *Al* and *Zr* seem to be the most practical candidates.

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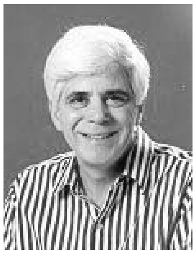

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